The High Frequency Instrument of Planck: Requirements and Design

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Abstract. The Planck satellite is a project of the European Space Agency based on a wide international collaboration, including United States and Canadian laboratories. It is dedicated to the measurement of the anisotropy of the Cosmic Microwave Background (CMB) with unprecedented sensitivity and angular resolution. The detectors of its High frequency Instrument (HFI) are bolometers cooled down to 100mK. Their sensitivity will be limited by the photon noise of the CMB itself at low frequencies, and of the instrument background at high frequencies. The requirements on the measurement chain are directly related to the strategy of observation used for the satellite. Due to the scanning on the sky, time features of the measurement chain are directly transformed into angular features in the sky maps. This impacts the bolometer design as well as other elements: For example, the cooling system must present outstanding temperature stability, and the amplification chain must show, down to very low frequencies, a flat noise spectrum.

INTRODUCTION

The most distant, and therefore the most ancient source of radiation that can be directly observed from Earth is the Cosmic Microwave Background (CMB). The satellite COBE has measured its submillimeter emission, which is that of a nearly perfect blackbody at 2.73K. This emission is attributed to the primordial universe when it was about 300 000 years old and warm enough (3000K) to ionize the hydrogen gas that constitutes most of its mass. Due to the expansion of the universe, this radiation was red-shifted by Doppler effect by a factor of about 1000, and thanks to the cooling due to the expansion, it could travel and reach us through the very transparent neutral hydrogen. The discovery of the CMB and its refined observation by COBE are pillars that support the big bang theory. The CMB is isotropic over the sky down to a level of 10^{-5} at small scales. The tiny deviations from uniformity give us unique information on the physics of the primeval universe, on the cosmological parameters describing the geometry of the universe, and on the history of matter and radiation since the Big Bang and up to our times.

New results from the balloon-borne experiments BOOMERanG [1] and MAXIMA [2] and from ground-based experiments using radio detectors and interferometry were recently published [3], [4]. They gave a first view of the small scale anisotropy of the CMB, unveiling the predicted peaks in the power spectrum of its angular distribution.

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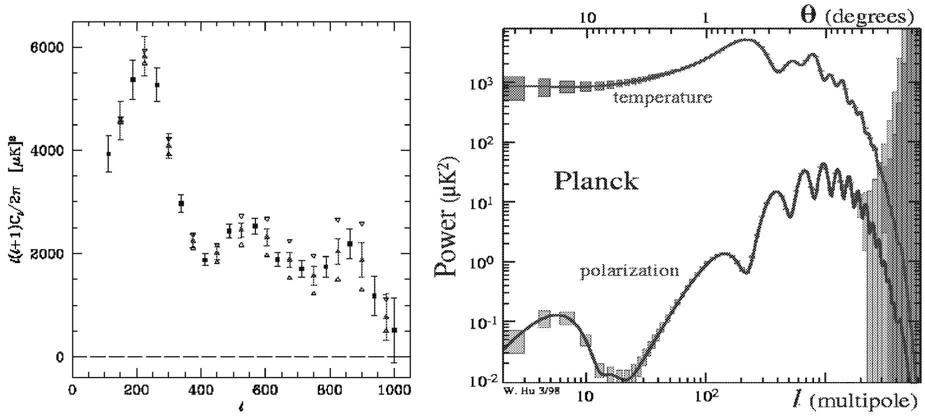

FIGURE 1. Left (a): The power spectrum of CMB anisotropies as seen by BOOMEranG. The first peak corresponds to an angular scale of about 1 degree as predicted for a "flat Universe" (i.e., a Universe where the spatial part of the metric is Euclidean). (b): Simulation of the Planck capability in the domain of angular frequencies. Smaller details will be measured with a much better sensitivity (wrt BOOMERanG) on the whole sky. The position of the first peak informs us on the curvature of the universe, while the whole spectrum give much more about other cosmological parameters.

Following COBE, NASA launched in the summer of 2001 the MAP satellite which will be a second generation CMB space experiment. The detectors are uncooled radio-type receivers with a sensitivity comparable to the balloon-borne bolometer experiments but with significantly better capabilities for large scale measurements and control of systematics.

The 'Planck' project of the European Space Agency, to be launched in 2007, is intended to be the third generation of CMB space experiments, pushing to its limits the knowledge that will be retrieved from the CMB observation with unprecedented angular resolution and sensitivity.

HFI PERFORMANCES

The high frequency instrument (HFI) covers the frequency range between 100 and 1000GHz with an angular resolution of about 5 arcmin in for of its six spectral bands. Its sensitivity will be limited, in the CMB channels, by the statistical fluctuations [5] of the CMB itself [6], which makes it a kind of ultimate experiment. It will also measure the polarization of the CMB in three channels, which will give independent and unique information on the CMB anisotropy [7]. The I, Q and U Stokes parameters will be measured thanks to four independent bolometers sensitive to polarizations separated by 45° from each other.

The accuracy on the CMB can be achieved only by removing the various foregrounds formed by the evolving universe situated between us and the warm primordial universe emitting the CMB. Among these, we see the emission of dust and gas in our own galaxy and from other galaxies. Clusters of galaxies, that contain high temperature gas detected in the X-rays, distort the CMB by inverse Compton scattering. This is the Sunyaev-Zeldovich Effect (SZE), that makes clusters of galaxies good tracers of the dynamics of the universe at large scales. Six bands in the HFI and four more in the LFI are needed to separate these various components thanks to their spectral and spatial signature. An additional benefit of the increase in complexity resulting from this approach is that all these astrophysical sources will be known much better, which is in many cases of major interest for astronomy and an important motivation for the HFI science team.

TABLE 1. Planck HFI performances.

Central Frequency	**(GHz)**	**100**	**143**	**217**	**353**	**545**	**857**
Beam Full width Half Maximum	arcmin	9.2	7.1	5.0	5.0	5.0	5.0
Number of unpolarized detectors		4	4	4	4	4	4
Number of polarized detectors		-	8	8	8	-	-
Total sensitivity (•T/T)	μK/K	2.2	2.4	3.8	15	80	8000
U and Q sensitivity (•T/T)	μK/K	-	4.8	7.6	30	-	-
Flux sensitivity	mJy	9.0	12.6	9.4	20	46	52
YSZ per FOV (x10^6)		1.2	2.1	440	6.4	32	730

Planck has to be considered not only as the third generation of CMB satellites, but also as the first sub-Terahertz sky survey of modern astronomy. Several thousands of galaxies, of young stellar objects, of clusters of galaxies will be observed in a new way. Nearly every field of astronomy will benefit from its results, from the study of the solar system (Trans-Neptunian objects for example) to the large scale structure of the universe (SZE results), as well as new insight on the cold components of galaxies, a possible candidate for dark matter. The Planck project is committed to deliver a set of well-defined products to the scientific community at large and will be one of the inputs of the future virtual observatories of the future.

DESIGN OF THE HFI SYSTEM

The Planck orbit will be a "halo" orbit around the L2 Lagrangian point of the Sun-Earth system, at about 1.5 million km of the Earth (figure 2). The satellite will rotate at 1RPM around an axis nearly anti-solar, allowing its field of view to scan large circles in the sky. Every 60min, the axis of rotation will be shifted by 2.5 arcmin, in order to follow the movement of the Earth around the Sun. In six months the successive circles will cover the full sky with unequal integration times.

The useful data from the telescope is therefore a quasi-periodic signal, with a period of one minute. The signal from the detection chain must therefore be stable from one observation of a source to the next one [8]. Lower frequencies can be filtered out in the data reduction process. This stability is a major requirement for the cryogenics and the electronics of HFI. The scan rate is 6deg/s. With 5 arcmin beams, the response time of the bolometers must be less than a few milliseconds. This is the driving requirement for the choice of the bolometers. In particular, it was understood from the beginning of the project that only very low temperature (100mK or less) would allow to reach this speed for the large bolometers needed in the millimeter range. This choice is consistent with the requirement that the sensitivity must be limited by the photon noise in the HFI wavelength range.

TABLE 2. Required bolometer performances.

Frequ. (GHz)	Optical Load (pW)	Maximum NEP $10^{-17}WHz^{-1/2}$	Goal time constant (ms)	Maximum time constant (ms)
100	1.0	1.2	3.9	7.8
143	1.1	1.5	2.9	5.7
217	1.1	1.8	2.2	4.4
353	1.0	2.2	2.2	4.4
545	5.0	6.0	2.2	4.4
857	16.0	13.5	2.2	4.4
143P	0.57	1.1	3.0	5.7
217P	0.54	1.3	2.2	4.4
545P	2.50	4.3	2.2	4.4

The absorber of the bolometers is of the Spider web type [9] for unpolarized detectors. For polarized channels; the bolometers are sensitive to polarization, thanks to an absorber made with parallel wires (J. Bock). NTD Ge thermometers with impedance of about 10MΩ are the sensitive elements. The required performances are listed in table 2.

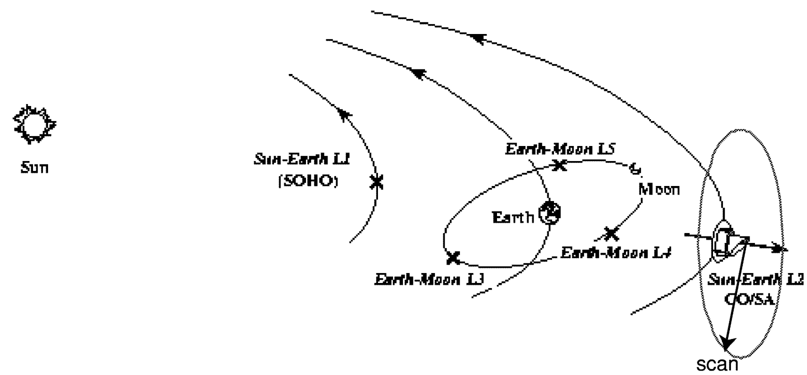

FIGURE 2. Schematic representation of the Planck orbit and scanning strategy. The readout electronics must not be the limiting factor of the detection chain. A specially developed amplifier [10] using tunable AC bias and cold J-FET preamplifier shows a $5nVHz^{-1/2}$ noise down to 10^{-2} Hz (fig.3).

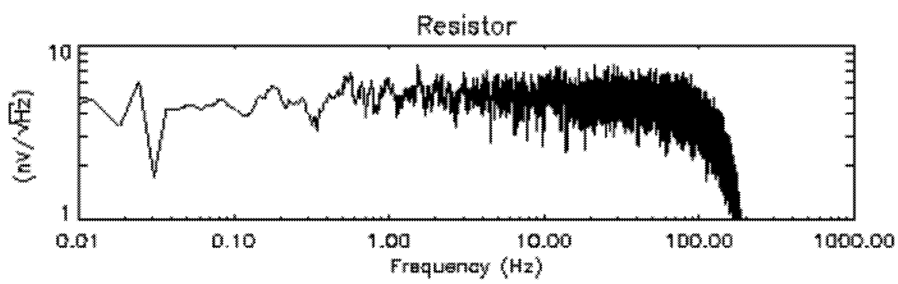

FIGURE 3. Noise spectrum of the readout electronics

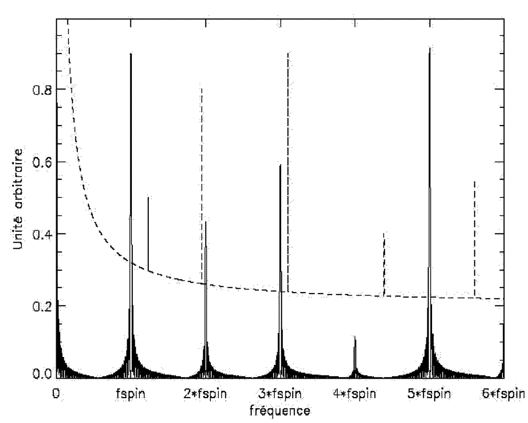

FIGURE 4. The scientific signal is periodic at the frequency of the spin rate of the satellite (1RPM). The first 5000 harmonics contain useful information, which determines the working frequency range of the bolometers: from 0.016Hz to about 100Hz.

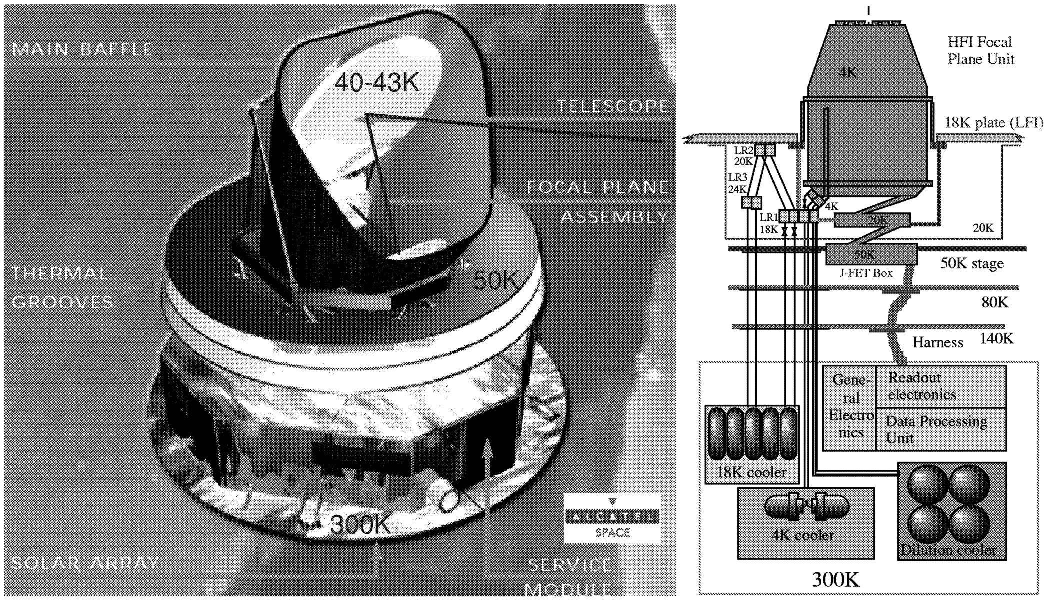

FIGURE 5. Left: The solar panels cover the bottom part of the satellite. The thermal architecture allows to passively cool the telescope down to 40K. Right: Three different active coolers are needed to cool the bolometers down to 0.1K.

Thermal requirements have been the driver for the design of the Planck Satellite. Thanks to its stable orientation with respect to the sun, the moon and the earth, it was possible to obtain an efficient passive cooling of the science payload down to 50K or less (see figure 5).

Coolers based on J-T expansion of hydrogen and sorption pumps cool both LFI and HFI down to 20K. The J-T valve delivers a mixture of liquid and gas at about 17.5K. A first high efficiency heat exchanger pre-cools the fluids for the coolers at lower temperature. Mechanical compressors provide helium for the 4K J-T compressor. This is used to cool the whole focal plane unit of the HFI. Such a low temperature was needed to keep to low values the background radiation reaching the bolometers. The open loop helium3/helium4 dilution cooler provides both the cooling of the bolometers down to 100mK and cools an intermediate stage at 1.6K by J-T expansion of the helium mixture.

The internal architecture of the HFI focal plane unit is shown on figure 6. This architecture, based on a classical Russian dolls design, is essential to the proper operation of HFI. As shown on the right section of figure 6, radiation from the various stages loads the bolometers. This radiation must be very stable, because any fluctuation in the range of useful frequencies (0.016 to 100Hz) could be taken as coming from the sky. This implies very good temperature stability of the various stages of the HFI-focal plane unit: $20\mathrm{nKHz}^{-1/2}$ for the 100mK stage (directly connected to the bolometers), $28\mu\mathrm{KHz}^{-1/2}$ for the 1.6K stage, and $10\mu\mathrm{KHz}^{-1/2}$ for the 4K stage.

The amount of consumables of the 0.1K cooling system is the limiting parameter for the duration of the mission of Planck-HFI, which is nominally of 14 months.

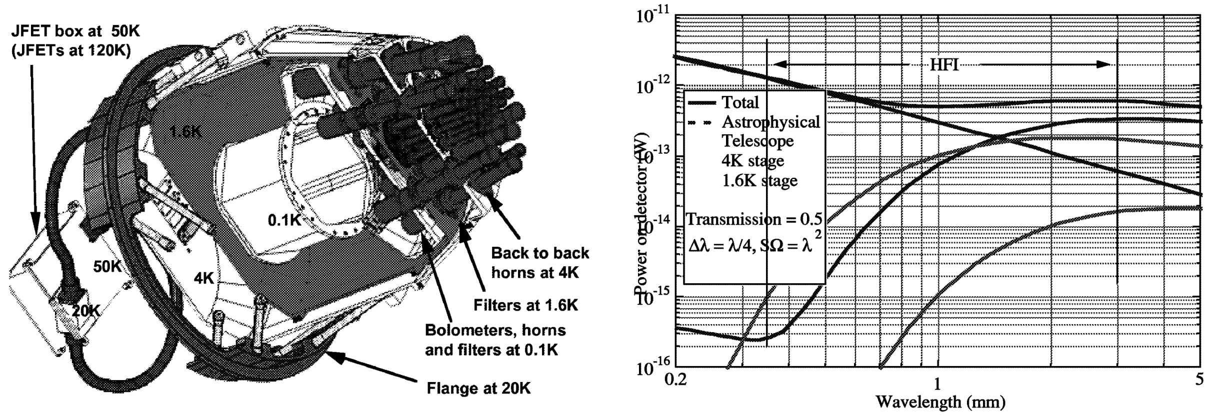

FIGURE 6. The focal plane unit of the HFI consists of three stages at 4K, 1.6k, and 0.1K. The coupling of the bolometer with the telescope is made thanks to corrugated horns at 4K. These stages radiate on the detectors and contribute to the background as well as the telescope (right).

CONCLUSIONS

Photon noise of the CMB radiation itself limits the sensitivity in the three most sensitive channels. Fundamental fluctuations of the flux reaching the detectors are therefore the main parameter limiting the instrument sensitivity. The only way to increase the sensitivity of such an instrument is to significantly increase the number of detectors. The scanning strategy plays a major part in the derivation of the instrument specification, since it gives, for signal and noises, the relation between the time domain and the domain of angular scales. A study of the bolometer requirements in the Fourier domain proved to be an efficient tool for several aspects of the instrument design.

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